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RESEARCH MEMORANDUM

AN INITIAL EXPERIMENTAL STUDY OF THE EFFECT OF VARIATIONS IN FREQUENCY AND IMPULSE ON THE REDUCTION IN TEMPERATURE RECOVERY FACTOR AFFORDED BY LARGE-SCALE UNSTEADY FLOW

By Robert R. Howell

Langley Aeronautical Laboratory
Langley Field, Va.

NATIONAL ADVISORY COMMITTEE
FOR AERONAUTICS
WASHINGTON
January 22, 1958

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SUMMARY

An experiment has been made of the reduction in temperature recovery factor afforded by large-scale unsteady flow wherein the frequency of the pulsating motion and the magnitude of the impulse required to generate it were each independently controlled. The unsteady flow was generated in this case by pulsing air from a forward-facing annular slot near the nose of a body of revolution. The tests were conducted in the Langley 9- by 12-inch supersonic blowdown tunnel at a Mach number of 1.96.

The results of the experiment indicated that the cooling afforded by the unsteady flow was primarily a function of the magnitude of the average pressure impulse per unit time used to generate the flow. For this particular apparatus the cooling appeared to be independent of the frequency at pulsing frequencies above about 1,000 cycles per second.

INTRODUCTION

One of the foremost aerodynamic problems facing the designer today is the problem of satisfactorily cooling vehicles in supersonic flight. A number of ideas have been proffered from which solutions to this problem may ultimately be obtained. One of these ideas suggests the possible use of large-scale unsteady flow to obtain the cooling. Experimental studies (see, for example, references 1 to 3) have demonstrated that cooling can be obtained from such unsteady flow. In addition, different analytical approaches by Ackeret (ref. 4) and Busemann (unpublished) have both shown that the cooling afforded by unsteady flow has a possible theoretical basis which is acceptable.

Although it is indicated that this approach to the heating problem is feasible, little is known to date of the relative importance of the number of variables which could affect the amount of cooling afforded by the unsteady motion. Accordingly, an experiment was set up with which it was hoped to obtain a better understanding of the relative importance of two of the more prominent variables - namely, the frequency of the unsteady motion and magnitude of the impulse required to generate it. In this case, the unsteady flow was generated by pulsing air from an annular slot near the nose of a body of revolution. It was visualized that the flow so generated would be in the form of toroidal rings encircling the body in a plane perpendicular to the stream direction. This particular experiment dealt exclusively with the variation of the amount of surface cooling or temperature recovery factor and was not concerned with solving the problem of practical application of this concept. It was carried out in the Langley 9- by 12-inch supersonic blowdown tunnel at a Mach number of 1.96.

SYMBOLS

A_f maximum frontal area of the body

A_s exit area of the annular slot

F force, lb

f frequency, cycles per second

M Mach number

$\frac{m_s}{m_\infty}$ ratio of mass flow through slot to mass that would flow through the slot area at free-stream conditions, $\frac{\rho_s V_s A_s}{\rho_\infty V_\infty A_s}$

N_{Pr} Prandtl number, 0.733 for air

p_s pressure in plenum chamber (total)

$\Delta\bar{p}_s$ average total pressure per pulse, $\frac{1}{t}\int_0^t \Delta p_s \, dt$ (where t is time for flow through slot)

$p_{t,\infty}$ free-stream total pressure

r body radius

T_t total temperature of free stream, $^{\circ}R$

T_v total temperature of the flow to the valve, $^{\circ}R$

T_w local skin temperature, $^{\circ}R$

t time, sec

V velocity

x longitudinal distance measured from model nose

Γ circulation, ft^2/sec

η_r temperature recovery factor, $\dfrac{T_w - T_\infty}{T_t - T_\infty}$

ρ mass density

Subscripts:

s conditions at slot exit

∞ free stream

MODEL AND INSTRUMENTATION

As was mentioned previously, the present unsteady flow was generated by pulsing air from an annular slot near the nose of a body of revolution, the ordinates for which are given in table I. Figure 1 shows a diagrammatic sketch of the apparatus used. The mechanism used to pulse the air through the slot was a rotating valve which was supported by two radial ball bearings and rotated about the axis of the body. The rotational speed of the valve was controlled by regulating air pressure to the two small air jets which drove a small air turbine attached to the valve. Air under controlled pressure was fed to the valve through a labyrinth seal arrangement. As the valve ports opened, the air flowed through the ports into a small annular plenum chamber and thence discharged to the outside through the annular slot. The details of the slot are presented in figure 2. As can be seen, independent control of the rotational speed of the valve and of the air supplied to it afforded independent control of the frequency as well as the magnitude

of the pulses from the slot which, of course, can be reduced to an average impulse (force × time).

The eight valve ports, which opened and closed simultaneously, were designed to allow flow 40 percent of the time and to prohibit flow the remaining 60 percent of the time so that the plenum chamber would discharge rather completely between pulses. The rectangular shape of the ports afforded a triangular-saw-tooth flow pattern with time.

A rapid-response variable-inductance-type pressure pickup was installed with the sensing element in the plenum chamber for the purpose of measuring the variation of chamber pressure with time. This particular pickup was developed by the Langley Instrument Research Division and has a flat frequency response to about 3,000 cycles per second, which was near the maximum fundamental frequency for these experiments.

The 0.030-inch-thick aluminum outer skin of the body was thermally insulated from the rest of the apparatus by supporting it at either end with Lucite supports. The air space between the skin and the tube which housed the valve was sealed so that none of the air flow to the valve or air turbine could enter. In addition, the space was filled with a fiber glass insulating material to reduce any convection which might result from a difference in temperature between the skin and the tube.

Thermocouples were tack-welded to the inner surface of the skin for the purpose of determining the longitudinal temperature distribution of the skin. A thermocouple was also installed in the airline leading to the valve for the purpose of measuring the total or stagnation temperature of the air entering the valve.

METHODS

The frequency of the pulses from the slot was determined by connecting the output of the internal pressure pickup to the vertical input of an oscilloscope and a controlled frequency to the horizontal input; through variation of the controlled frequency a Lissajous pattern was established on the oscilloscope.

The variation of the total pressure in the plenum chamber with time was measured from the oscillograph record of the pickup output. The pickup, as was previously noted, had a flat frequency response up to about 3,000 cycles per second and was, of course, calibrated in terms of oscillograph trace deflection. The accuracy of the pressures so measured appeared to be correct within ±0.2 pound per square inch. The longitudinal temperature distribution of the outer skin of the apparatus was measured by connecting the thermocouples attached to the skin to two

12-channel potentiometer-type temperature-recording instruments. These instruments recorded at the rate of one channel per second. The thermocouples were staggered to the two instruments, which recorded simultaneously, so that a complete temperature distribution plus the required reference temperatures were recorded every 12 seconds. It is believed that the accuracy of the temperature measurements was of the order of $\pm 1^{\circ}$.

TESTS

Prior to making wind-tunnel tests, bench tests were made to determine the quality of the pulses from the slot. A pickup similar to the one installed inside the apparatus was mounted externally 1/16 inch from the slot to determine whether the flow discharged uniformly along the slot and whether the inside pickup gave a correct indication of the variation of the total pressure in the plenum chamber with time. As a result of these tests, it was found necessary to limit the slot width to 0.03 inch or less to insure a discharge that was uniform along the slot to within 1 percent or less in total pressure. At greater slot widths, flow nonuniformity resulted from localized flow concentration near the valve ports. With the 0.03-inch-wide slot, it appeared from oscillograph records that the plenum chamber discharged completely between pulses for frequencies less than about 1,300 cycles per second. At higher frequencies, there was a small residue or steady pressure present. It was subsequently found that the presence of this steady pressure was relatively unimportant, as will be discussed in the section entitled "Results and Discussion." Typical oscillograph traces of the pressure-pickup output are shown as figure 3.

The wind-tunnel tests were conducted in the Langley 9- by 12-inch supersonic blowdown tunnel at a Mach number of 1.96 and at a Reynolds number of about 7×10^{6} per foot. The apparatus was mounted in the tunnel with its center line on the axis of the tunnel. (See fig. 4.) In order to insure that the measurements of the temperature of the skin were for the case of stable temperature conditions, flow was established in the wind tunnel and the temperature recorders were observed until the indicators stopped their motion; then, the temperature distribution was recorded twice. Inasmuch as the two distributions were recorded 12 seconds apart, a comparison of them would indicate the presence of any appreciable variation of temperature with time.

From the preliminary exploratory tests, it was observed that a number of factors could influence the measured temperature distribution. First, any difference between the total temperature of the stream and the total temperature of the flow to the valve resulted in a difference

in the measured skin temperature. A calibration of this effect is presented in figure 5 where the recovery factor for the first thermocouple downstream of the slot is presented as a function of the ratio of the two total temperatures for two combinations of frequency and average pulse pressure ratio. In order to alleviate this effect, the flow to the valve was passed through a cooler to bring its total temperature down to near the operating total temperature of the tunnel. With this temperature fixed, the tunnel was started and run until the two total temperatures, that is, the total temperature of the stream and the total temperature of the flow to the valve, were within 5° of each other before data were taken. In order to correct for the small remaining difference in temperature (approximately 1 percent maximum), the skin temperature was adjusted to correspond to that of $\frac{T_v}{T_t} = 1.0$ (fig. 5), assuming the slope of the curves presented was constant for all of the combinations of frequency and average pulse force tested.

A second possible error that could affect the measured temperature of the skin is the effect of heat transfer lengthwise through the skin as a result of the temperature gradient that existed along it. In order to examine the possible magnitude of the differences in measured skin temperature and local equilibrium temperature, differential equations defining the longitudinal distribution of temperature in the skin were set up. Consideration was made not only of the heat conduction through the skin itself but also of the conduction from the skin to the air. It was assumed that a linear equilibrium-temperature distribution existed in the fluid outside the tube and calculations were made of the corresponding local temperatures in the skin. It was indicated that a maximum temperature difference between the local equilibrium temperature and skin temperature could be no greater than 5° or about 1 percent. Inasmuch as it would affect an increase in temperature at the cooler upstream end of the skin, this change is in the direction to make the experimental measurements of cooling conservative.

Another possible source of error is the possible change in total temperature of the air passing through the valve which could result from the air doing work on the valve or the valve doing work on the air. Of most concern is the possibility of the air being cooled by doing work on the valve. It was found from tests that, in order to maintain a given frequency or rotational speed of the valve with increasing pressure to the valve (corresponds to an increase in axial load), increasing pressure to the drive jets was required. Additional tests were made to indicate the variation of the work associated with the friction in the bearings supporting the valve with various pressure or axial loads. It was found that, within the axial-load range imposed by these tests, the friction in the bearings was essentially constant after a slight initial axial load was applied. Inasmuch as the friction appeared to be constant for a set

rotational speed, it is indicated that the valve tends to do work on the air, which would result in an increase in the total temperature of the flow from the slot. This possible effect is in the direction to make the measurements of cooling further conservative. It should be noted that no quantitative measure of this effect was obtained. It is believed, however, to be very small.

RESULTS AND DISCUSSION

Presented in figure 6 are the longitudinal distributions of skin temperature in the form of recovery factor for the case of no flow from the slot and for two cases of steady flow from the slot. The recovery factor for the no-flow case agrees well with the turbulent-boundary-layer recovery factor calculated as $\sqrt[3]{N_{Pr}}$. The pressure coefficient as determined by measurements in the plenum chamber for this case was approximately 0.4 which corresponds roughly to the pressure on a forward-facing step (ref. 5). This result, of course, is attributable to the forward-facing-slot geometry.

The mass flow through the slot for the two steady-flow cases presented corresponds to about 3 and 5 times the maximum mass flow from the slot for the unsteady flow cases, which are discussed later. As can be seen, the reduction in recovery factor attributable to a steady discharge from the slot is small even for these high flow rates. At lower flow rates, the reduction was even less. It is concluded from these results that the steady or residue pressure in the plenum chamber, which was present for some of the unsteady-flow conditions, had no important effect on the cooling afforded by the unsteady flow. Also shown in figure 6 is a sketch of the body and the calulated bow shock as reflected from the tunnel walls. The reflected disturbances struck the body in a band starting at about 6 inches behind the nose. No definite effects attributable to this band of reflected disturbances were noted.

Typical distributions of recovery factor for various unsteady flows from the slot are presented in figures 7 and 8. The distributions presented in figure 7 were obtained with data as measured and are, therefore, uncorrected for differences in $\frac{T_v}{T_t}$ from the value of 1.0 (fig. 5). The distributions of recovery factor presented in figure 8 are the data shown in figure 7 corrected for the effect of the total-temperature differences by the method previously discussed. By comparison of the two figures, an insight as to the magnitude of this correction may be obtained.

As may be seen, various combinations of frequency and average pulse pressure ratio gave varying degrees of reduction in the temperature

recovery factor. As noted in the section entitled "Symbols," the numerator of the average pulse pressure ratio $\Delta\bar{p}_s/p_{t,\infty}$ was determined by averaging the variation of the increase in pressure in the plenum chamber (fig. 3) over the portion of the cycle that the valve was allowing flow through the slot. The denominator is, of course, free-stream stagnation pressure. This ratio, then, is the ratio of the average total pressure of each pulse to the stream total pressure.

The apparent general rise in recovery factor with an increase in downstream distance is probably to be expected inasmuch as the strength or energy content of any disturbance created by a pulse from the slot would diminish with downstream distance as a result of mixing. Reductions in recovery factor near the slot were generally accompanied by a much smaller reduction at the most rearward measuring point (approximately 6 inches rearward).

As indicated by these typical distributions, the minimum value of recovery factor attained in this experiment was not very low - approximately 0.8. This result was somewhat disappointing. Although the primary purpose of the experiment was to explore the relative importance of frequency and average pulse pressure on the cooling afforded by unsteady flow, it had been hoped that, by proper choice of the range of these variables, a large reduction in skin temperature could be obtained. Failure to achieve this goal, however, did not invalidate or obscure the primary purpose of the experiment. It is believed that the following analysis of the results obtained with the present apparatus clearly provides a better understanding of the relative importance of the two variables explored and tends to indicate a logical direction for future work.

Inasmuch as only skin temperature measurements were made, no attempt could be made to verify Busemann's unpublished analysis, which dealt primarily with changes in eddy heat conductivity and viscosity. It appeared, however, that the present results could be correlated on the basis of Ackeret's concept (ref. 4). Ackeret's concept, as it was applied in the reference paper to two-dimensional flow past a cylinder, was that the average reduction in surface temperature or recovery factor should be proportional to the product of the frequency at which the two-dimensional vortices were shed from the cylinder and the circulation contained in each vortex:

$$\Delta\bar{\eta}_r \propto f \times \Gamma$$

For the case in reference 4, of course, the shedding of the vortices generated the unsteady motion. It can be shown (see ref. 6, for example) that the circulation produced by a pulse from a slot such as was used in

the present experiment should be proportional to the impulse generated, that is,

$$\Gamma \propto F \times t$$

The time, in the present case, is inversely proportional to the frequency $\left(t \propto \frac{1}{f}\right)$ and the force is equal to the average pulse pressure times the exit area of the slot $\left(\Delta\bar{p}_s \times A_s\right)$. Upon substituting these terms into Ackeret's original equation

$$\Delta\bar{\eta}_r \propto f \times \Gamma \propto f \times \frac{\Delta\bar{p}_s A_s}{f}$$

it is seen that the frequency term disappears indicating change in average recovery factor is proportional to the force term only.

In correlating the data on this basis, the first datum point located 3/4 inch downstream of the slot was used. Actually, any other longitudinal station would have correlated equally well although the slope of the correlation would have been less.

The correlation made on the described basis is presented in figure 9 where the recovery factor at the chosen point is plotted as a function of the product of average pulse pressure and the slot exit area. This product is made nondimensional by dividing by the product of free-stream total pressure and the frontal area of the body. The different symbols correspond to different tests. Each test was made by maintaining an essentially constant pressure to the valve and varying the frequency. The resulting combinations of frequency and pressure pulse amplitude explored are indicated in figure 10. As can be seen from figure 9, the recovery factor does appear to vary fairly linearly with the force ratio $\frac{\Delta\bar{p}_s A_s}{p_{t,\infty} A_f}$ with the exception of the half-filled symbols. The half-filled symbols correspond to data points which were obtained at very low frequencies in an effort to see how low a frequency could be employed and still obtain a cooling effect. In order to show the effect which was observed, these data are cross-plotted as a function of frequency in figure 11, assuming for this case that the force ratio $\frac{\Delta\bar{p}_s A_s}{p_{t,\infty} A_f}$ is constant. It is seen that for the present apparatus it is apparently necessary to attain a frequency of approximately 1,000 cycles per second before the recovery factor becomes independent of frequency. It is not

believed that this apparent effect of frequency is a characteristic of the flow mechanics involved with the cooling but rather is associated with the rotating valve. When the valve rotational speed is slowed down to obtain the lower frequencies, the time that the valve ports are open is increased so that a pulse is relatively long and does not approach the idealized concept of an instantaneous impulse. At these low frequencies, then, the pulses do not create a maximum circulation.

The fact that the recovery factor does tend to vary linearly with the force ratio $\frac{\Delta\bar{p}_s A_s}{p_{t,\infty} A_f}$ is consistent with Ackeret's concept that the change in recovery factor should be proportional to the total circulation produced by the unsteady motion. The maximum value of the force ratio indicated for these experiments was fixed by flow limitations of the slot. The ratio of the slot area to body frontal area is for this case only 0.046. Further research is needed to determine whether the cooling will continue to increase linearly with further increases in $\frac{\Delta\bar{p}_s A_s}{p_{t,\infty} A_f}$.

CONCLUDING REMARKS

An exploratory experiment has been made of the reduction in temperature recovery factor afforded by large-scale unsteady flow wherein the frequency of the pulsating motion and the impulse generating it were each independently controlled. Although the range of impulse magnitude for the present case was not large enough to achieve large amounts of cooling, an insight as to the relative importance of these two variables was obtained.

It was found that the amount of cooling afforded apparently was a function of the average pulse pressure force only, provided the frequency was greater than about 1,000 cycles per second. This limit of 1,000 cycles per second is believed to result from the characteristics of the pulses generated by the machine used for these tests. Further research is needed to determine whether further increases in pulse pressure force will yield corresponding reductions in temperature recovery factor.

Langley Aeronautical Laboratory,
National Advisory Committee for Aeronautics,
Langley Field, Va., September 17, 1957.

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TABLE I

BASIC BODY ORDINATES

Basic body ordinates	
x, in.	r, in.
0	0
.1	.362
.2	.490
.3	.590
.4	.670
.6	.870
.8	.910
1.00	1.000
1.50	1.150
2.00	1.225
2.50	1.250
10.00	1.250

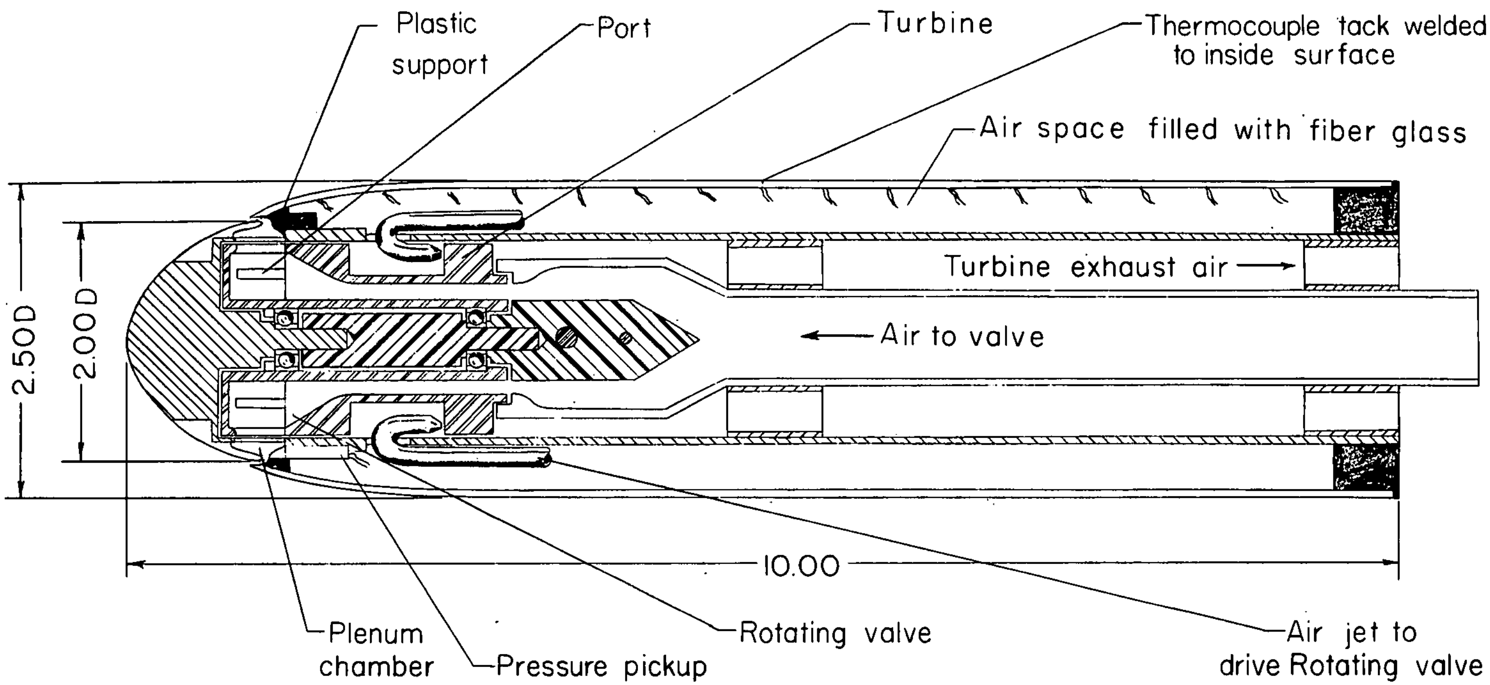

Figure 1.- Diagrammatic sketch showing general arrangement of the pulsing mechanism and overall model layout. All dimensions are in inches.

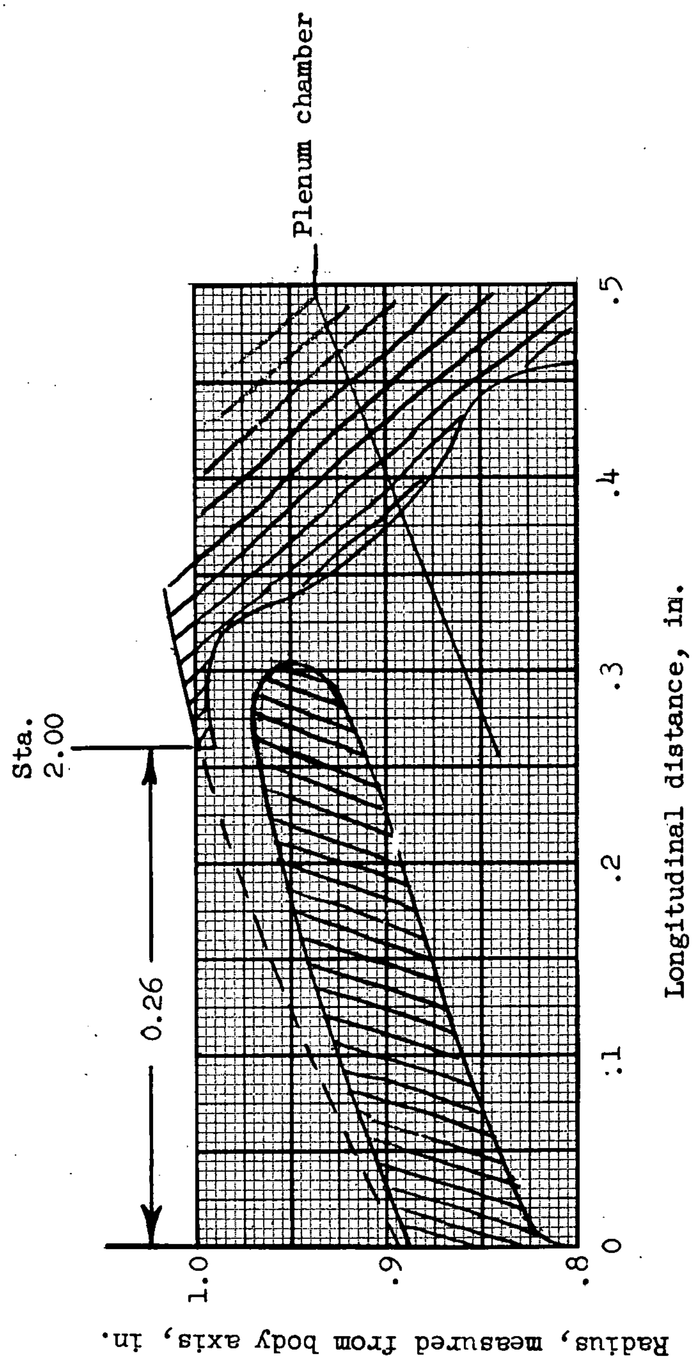

Figure 2.- Details of slot geometry. All dimensions are in inches.

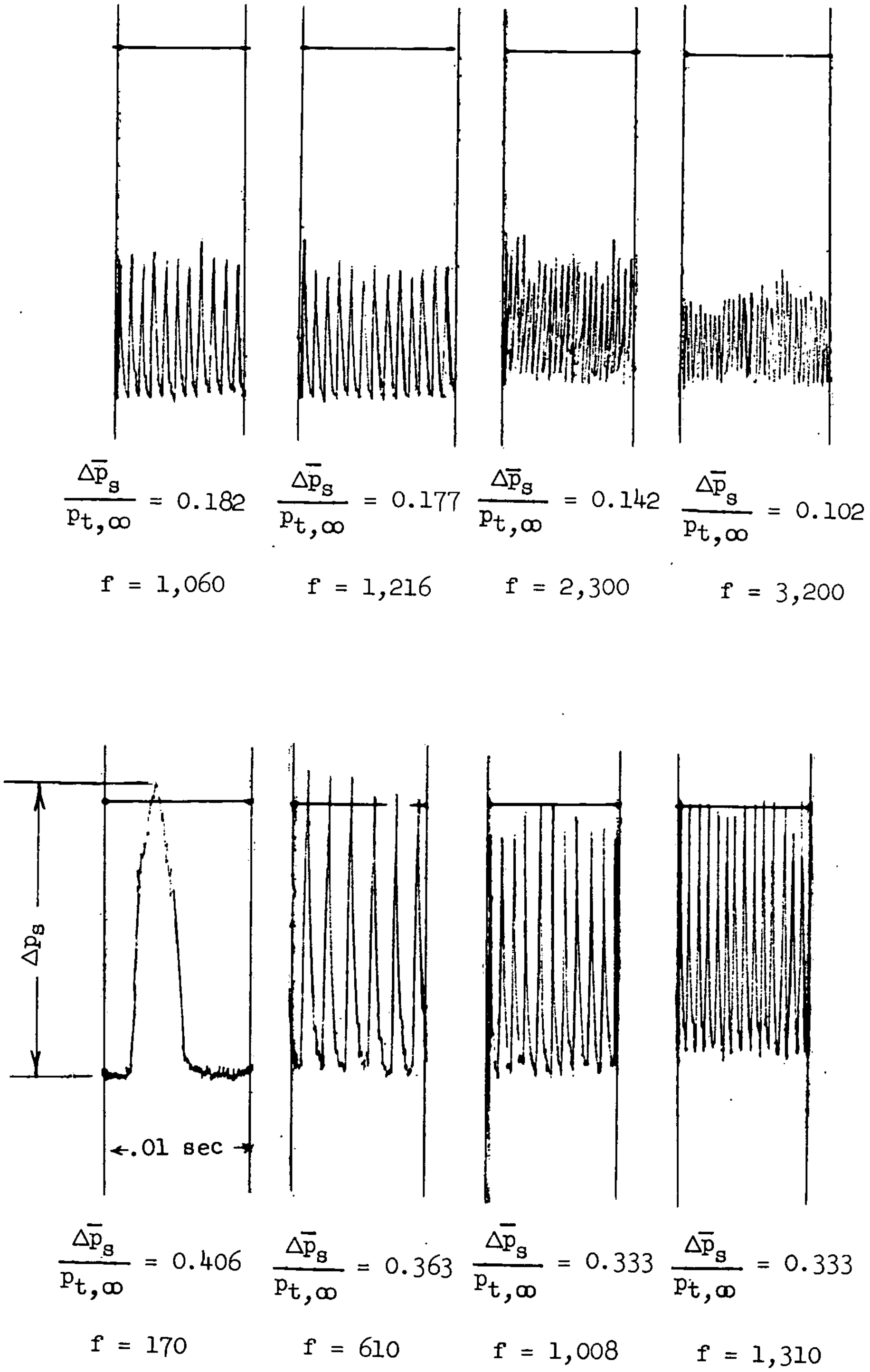

Figure 3.- Typical plenum-chamber pressure-time traces obtained as oscillograph records of the pressure-pickup output with tunnel running.

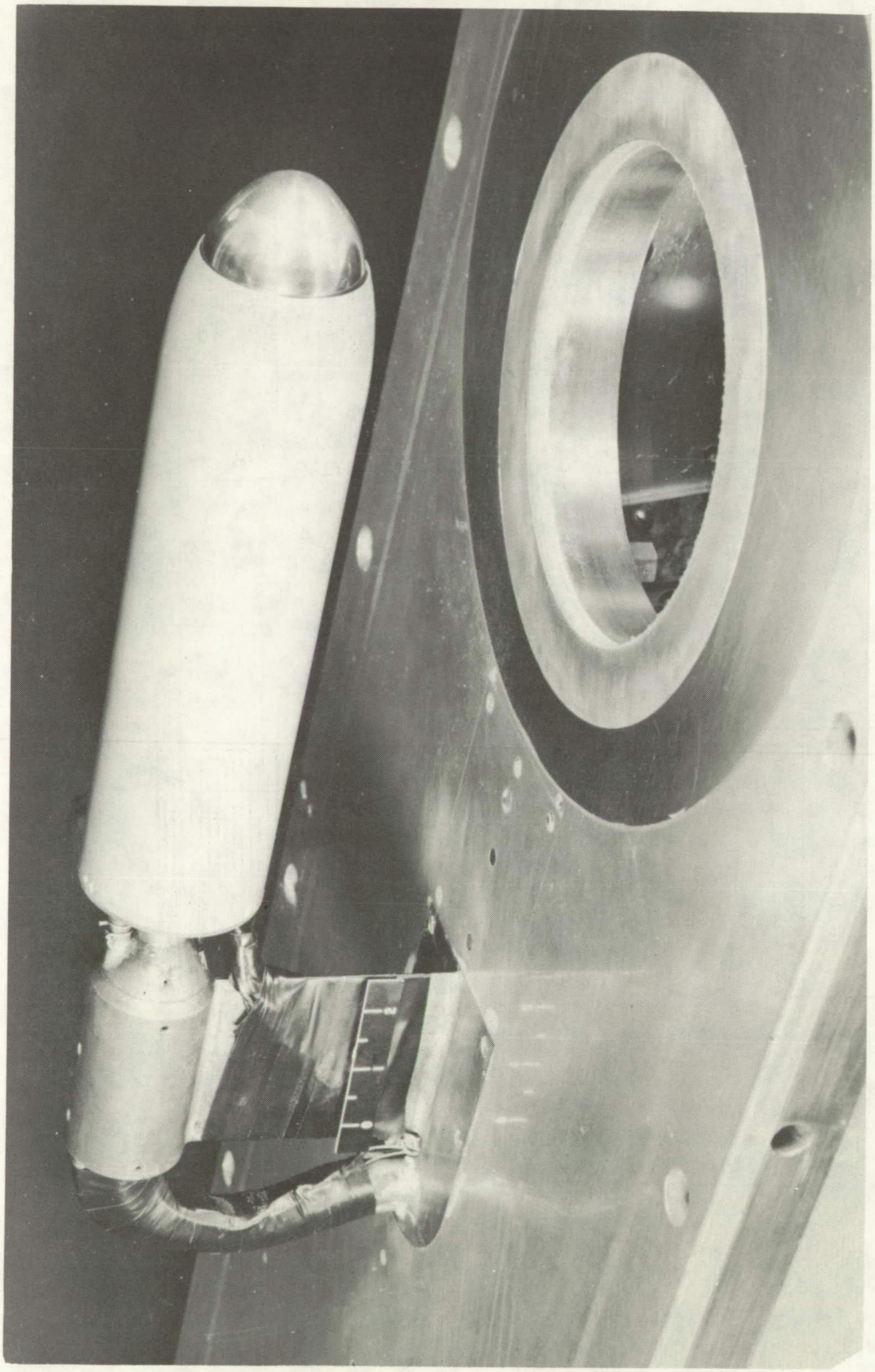

Figure 4.- Apparatus installed in the wind tunnel. L-57-496

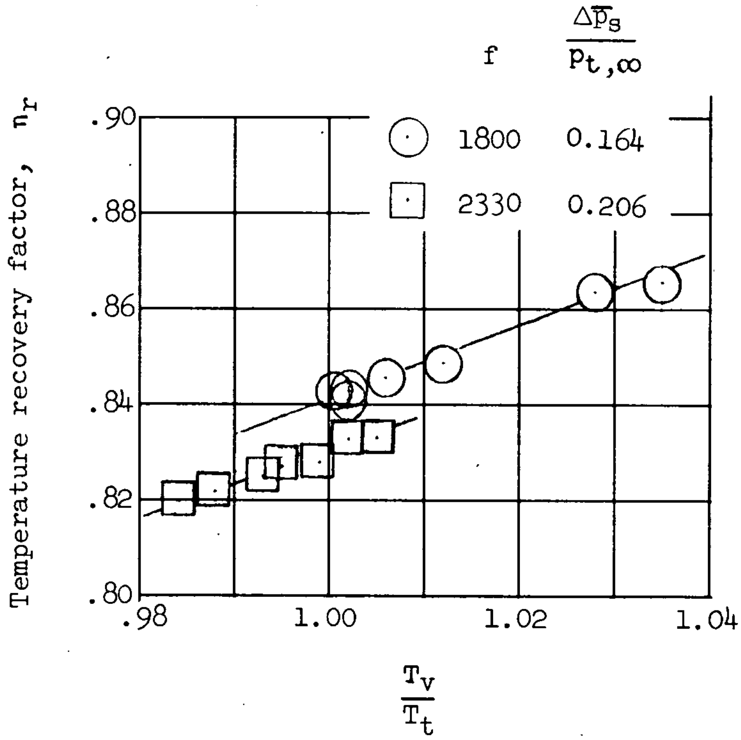

Figure 5.- The variation of temperature recovery factor with variation of the ratio of the total temperature of the valve flow to the total temperature of the stream at two unsteady slot flow conditions.

[redacted]

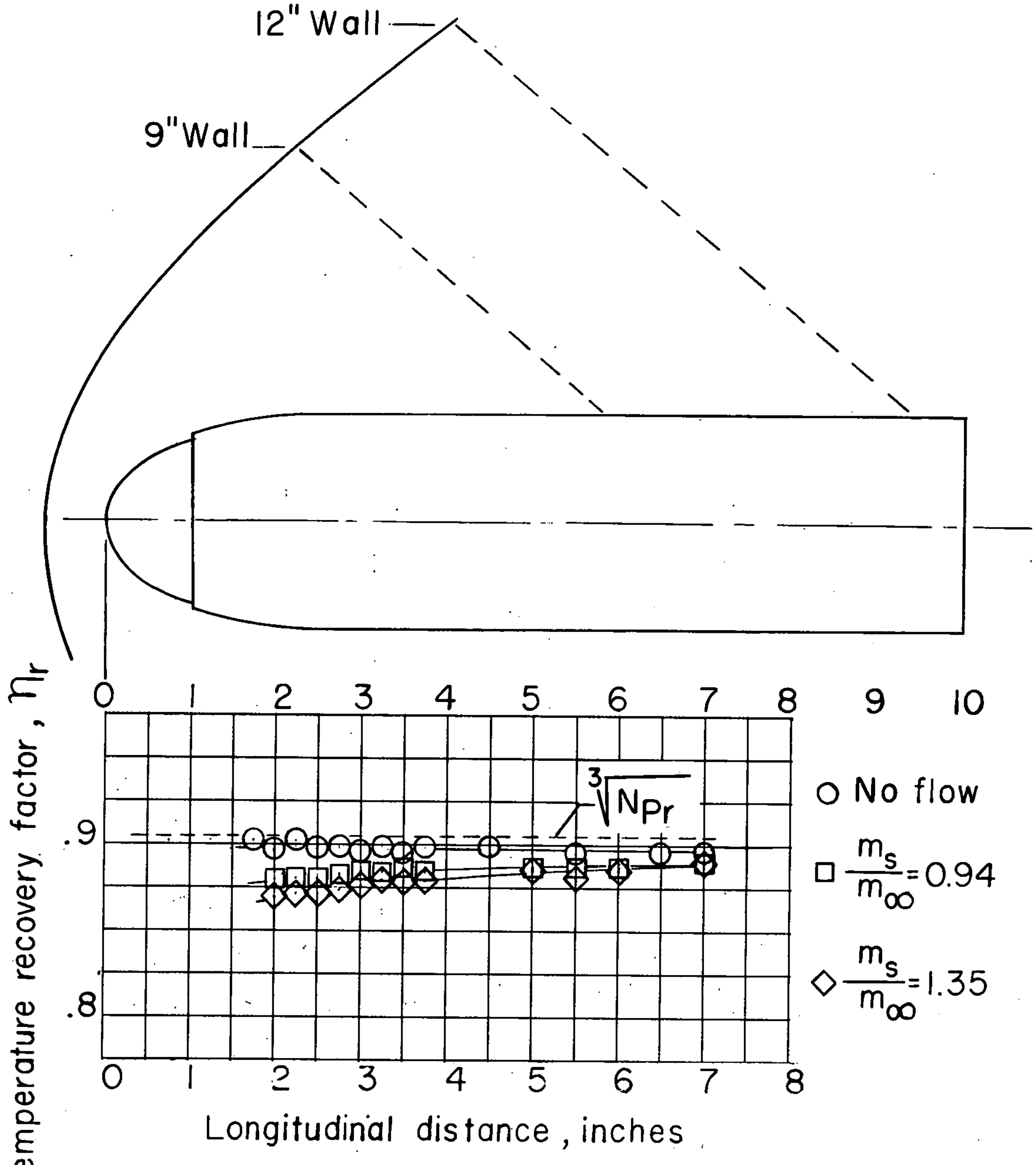

Figure 6.- Longitudinal distributions of temperature recovery factor for the case of no flow from the slot and for two cases of steady flow from the slot.

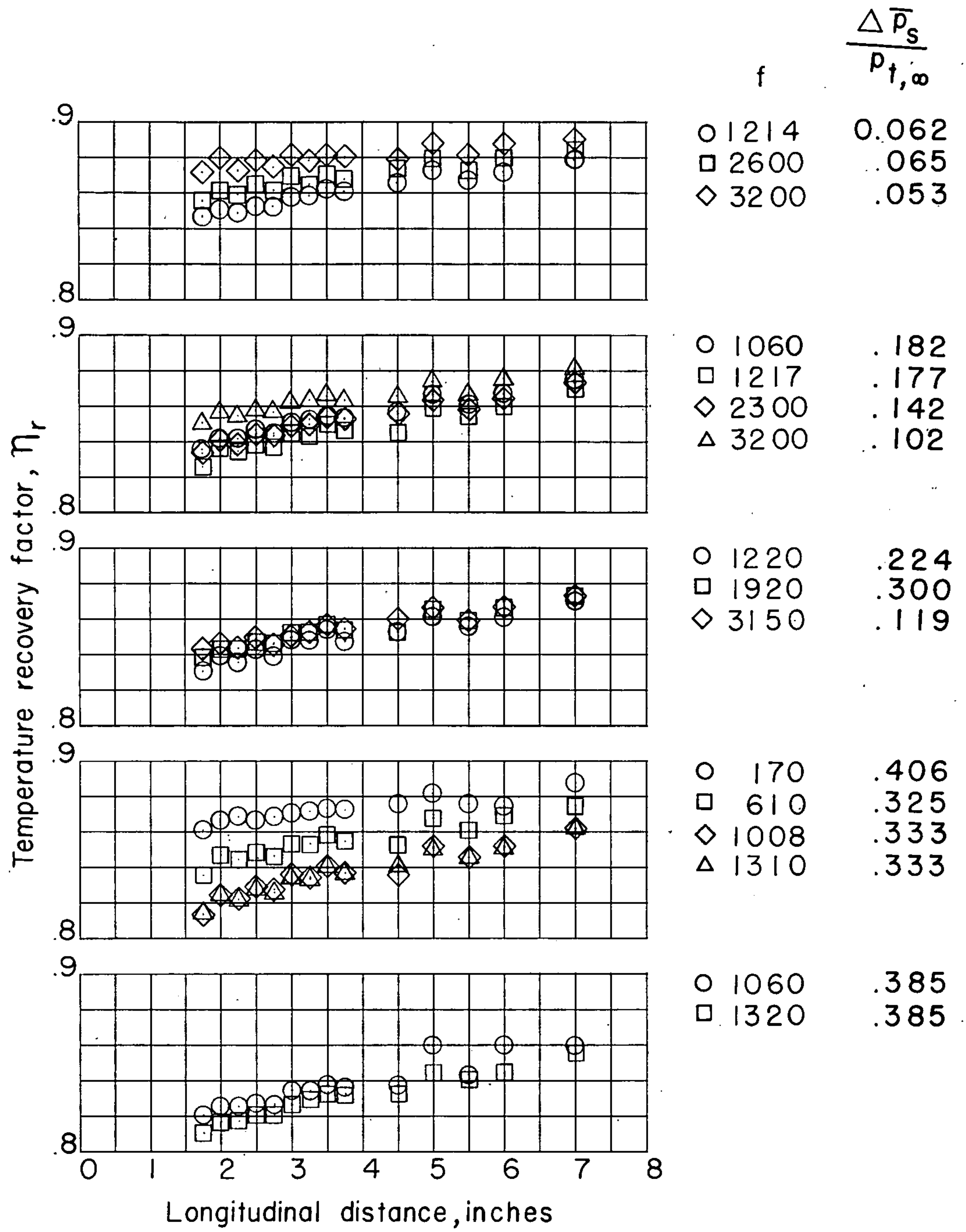

Figure 7.- Typical longitudinal distributions of temperature recovery factor for various combinations of frequency and average pulse pressure to free-stream total pressure ratio $\left(\text{uncorrected for } \Delta\frac{T_v}{T_t}\right)$.

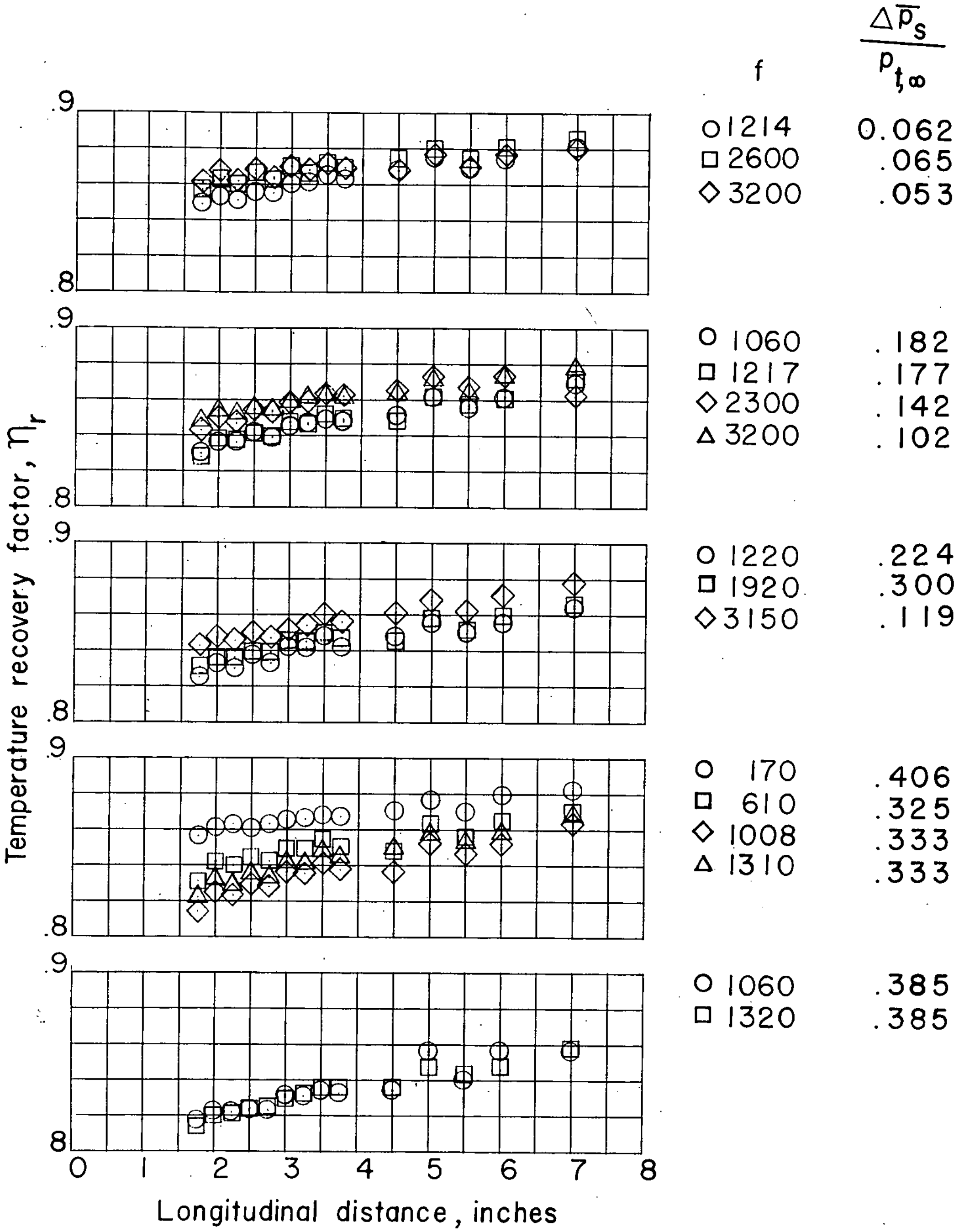

Figure 8.- Typical longitudinal distributions of temperature recovery factor for various combinations of frequency and average pulse pressure to free-stream total pressure ratio $\left(\text{corrected for } \Delta\frac{T_v}{T_t}\right)$.

[redacted]

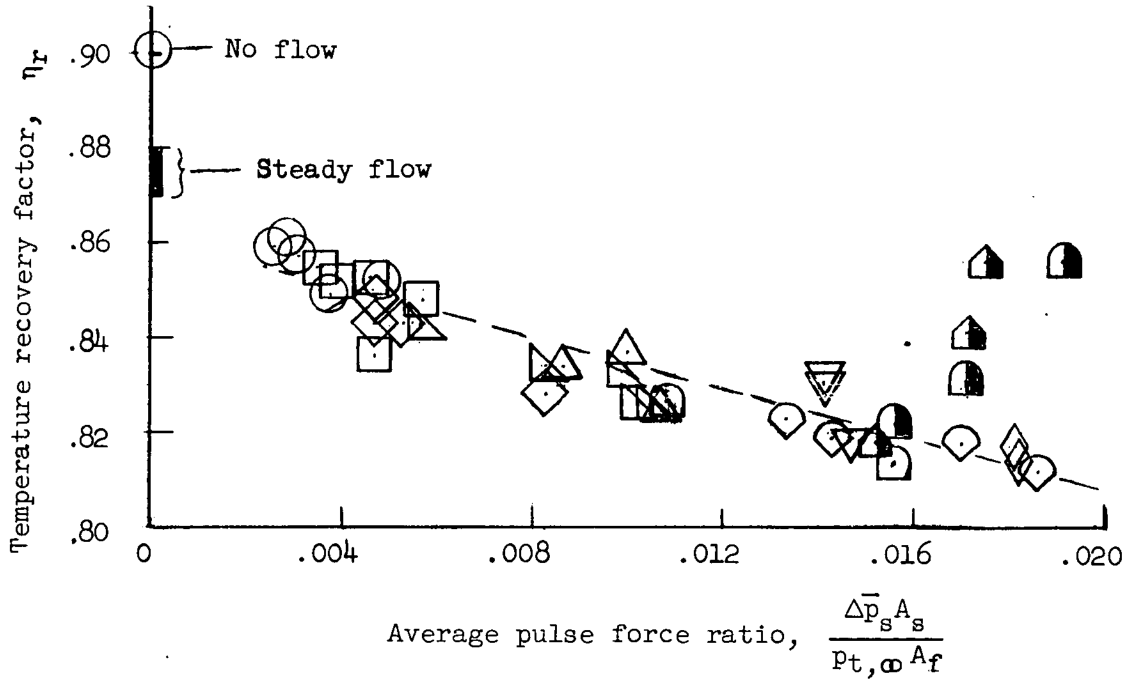

Figure 9.- Variation of temperature recovery factor with pulse force ratio $\frac{\Delta\bar{p}_s A_s}{p_{t,\infty} A_f}$. (Points having the same symbol were obtained during the same test.)

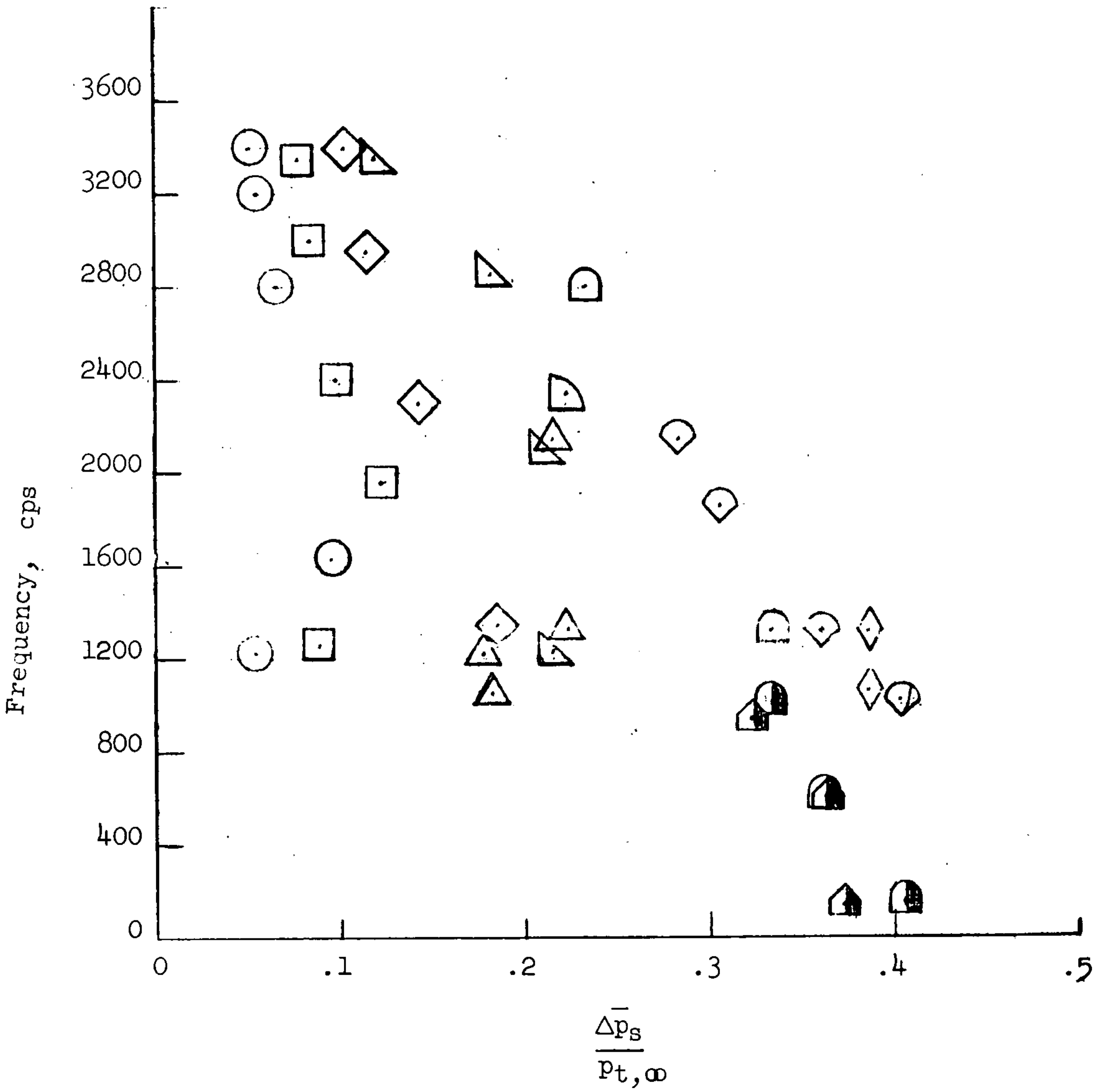

Figure 10.- Various combinations of frequency and average pressure pulse ratio tested in the unsteady-flow tests. (Points having the same symbol were obtained during the same test.)

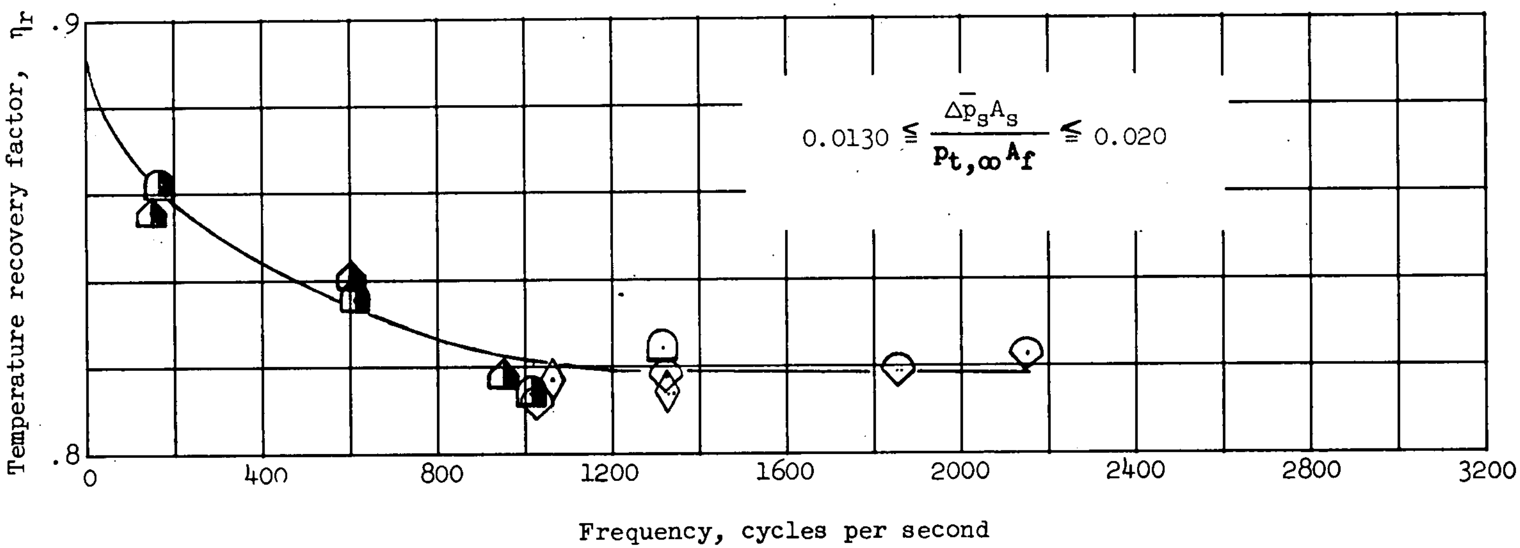

Figure 11.- Variation of recovery factor with the frequency of the unsteady motion for $\frac{\Delta\bar{p}_s A_s}{p_{t,\infty} A_f} \approx 0.017$. (Points having the same symbol were obtained during the same test.)

[redacted]

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